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Thermal optimization of an ice cream hardening process

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Abstract

The conservation of energy is an essential step that can be taken towards mitigating the issues of energy crisis and environmental degradation. Excessive use of energy and energy loss are usually associated with many industrial establishments worldwide-specially in the food processing industry, where a substantial amount of energy is consumed. Enormous potential exists for the cost effective improvement in existing energy consuming equipment. In the present work, an ice cream hardening machine for batch production is taken into consideration. The system consists of shell and tube condenser and evaporator coils as a part of primary refrigeration cycle along with the air blower. The optimization for the shape of ice cream boxes during hardening process is done. The combined effect of various parameters like velocity and temperature of blowing air, orientation of ice cream box and spacing between the ice cream boxes on the freezing time is studied to find the energy efficient and economic option. The results obtained by the theoretical model are evaluated by comparing with the experimental data.

Keywords: Freezing time, ice cream hardening, cooling load.

Nomenclature

C	Specific heat (kJ/kg K)
C_{lv}	Volumetric specific heat of unfrozen food (J/m^3 K)
C_{sv}	Volumetric specific heat of fully frozen food (J/m^3 K)
D	Slab thickness (m)
ΔH_{10}	Volumetric enthalpy difference between initial freezing point of food and -10 ˚C (J/m^3)
ΔH_{18}	Volumetric enthalpy difference between initial temperature of food item and -18 ˚C (J/m^3)
h	Surface heat transfer coefficient (W/m^2 K)
k_s	Thermal conductivity of frozen food (W/m K)
L_f	Volumetric latent heat of fusion (J/m^3)
P	Parameter defining the geometry of the food
R	Parameter defining the geometry of the food
t_f	Initial freezing point of the food (˚C)

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t_m	Freezing medium temperature (˚C)
T_c	Final centre temperature of food item (˚C)
T_i	Initial temperature of food item (˚C)
Greek symbols	
θ	Freezing time (s)

1. Introduction

Preservation of food is one of the most significant applications of refrigeration. It is known that cooling and freezing of food effectively reduces the activity of micro-organisms and enzymes, thus retarding deterioration. In addition, crystallization of water reduces the amount of liquid water in food items and inhibits microbial growth[1].

In order for cooling and freezing operations to be cost-effective, it is necessary to optimally design the refrigeration equipment to fit the specific requirements of the particular cooling or freezing application. The design of such refrigeration equipment requires estimation of the cooling and freezing times of foods and beverages, as well as the corresponding refrigeration loads.

Numerous methods for predicting the cooling and freezing times of foods[2] are available, including those based on numerical, analytical and empirical analysis. This paper focuses upon the method which is applicable to regularly shaped ice cream boxes. The performance of this method is evaluated by comparing their results to experimental freezing time data obtained from the literature.

The ice cream is cooled as quickly as possibly down to a holding temperature of less than -25°C. The temperatures and time of cooling will depend on the type of storage freezer, shape of packets, arrangement of packets, material of packets, flow rate of air and surrounding temperature. Rapid cooling will promote quick freezing of water and create small ice crystals, which ultimately increases the quality of an ice cream.

1.1. Packaging of an ice cream

Generally packaging of ice cream is done before hardening. In few cases it is done after hardening. When ice cream is drawn from the freezer, it is usually collected in containers, which give it the desired shape or size for convenient handling during hardening, storage and marketing.

The important requirements of packages for ice cream are:

- Protection against contamination
- Attractiveness
- Ease of opening and re-closure
- Ease of disposal

Desirable requirements of packages are:

- Protection against moisture
- Protection against temperature fluctuations

2. Theoretical model

2.1. Freezing time

Number of methods for predicting the cooling time and freezing time of foods are available, based on numerical, analytical, and empirical analysis. One of the most widely known simple methods for estimating freezing times of foods and beverages is developed by Plank[3]. In this method, convective heat transfer is assumed to occur between the food item and the surrounding cooling medium. In addition, the temperature of the food item is assumed to be at its initial freezing temperature and that this temperature is constant throughout the freezing process. Furthermore, a constant thermal conductivity for the frozen region is assumed. Plank's freezing time estimation is as follows:

$$\theta = \frac{L_f}{t_f t_m}\left[\frac{PD}{h} + \frac{RD^2}{k_s}\right] \tag{1}$$

Since this equation does not include the times below and above the freezing itself, several attempts have been made to improve it by adding new terms and parameters, to make it suitable for the entire freezing process.

Cleland and Earle[4] improved upon Plank's model by incorporating corrections to account for the removal of sensible heat both above and below the initial freezing point of the food as well as temperature variation during freezing. Regression equations were developed to estimate the geometric parameters, *P* and *R,* for infinite slabs, infinite cylinders, spheres and rectangular bricks. In these regression equations, the effects of surface heat transfer, precooling and final sub cooling are accounted for by means of the Biot number *Bi,* the Plank number *Pk,* and the Stefan number *Ste*. The latent heat L_f in Plank's equation is replaced with the volumetric enthalpy change of the food ΔH_{10} between the freezing temperature T_f and final center temperature assumed to be -10 ˚C. Thus, the modified Plank equation takes the form

$$\theta = \frac{\Delta H_{10}}{t_f - t_m}\left[\frac{PD}{h} + \frac{RD^2}{k_s}\right] \tag{2}$$

Hung and Thompson[5] obtained Plank-like formulas through the regression analysis of freezing data. Their equation incorporates the volumetric change in enthalpy ΔH_{18} for the freezing process as well as a weighted average temperature difference between the initial temperature of the food and the freezing medium temperature. This weighted average temperature difference ΔT is given as follows:

$$\Delta T = \left(t_f - t_m\right) + \frac{\left(T_i - t_f\right)^2 \frac{C_{lv}}{2} - \left(t_f - T_c\right)^2 \frac{C_{sv}}{2}}{\Delta H_{18}} \tag{3}$$

The freezing time prediction model is based on following equation:

$$\theta = \frac{\Delta H_{18}}{\Delta T}\left[\frac{PD}{h} + \frac{RD^2}{k_s}\right] \tag{4}$$

3. Experimental set up and methodology

3.1. Air blast freezer

Air blast freezer is a refrigerated space in which ice cream boxes are to be kept. The vapor compression system cools the refrigerant R 404a which flow through the cooling coil. Fans are provided to circulate the air. Air passes across the cooling coil, get cooled and flows through the arrangement of the ice cream boxes to cool them. Ice cream is taken to the temperature of -18 ºC. The schematic of an air blast freezer is shown in Fig 1.

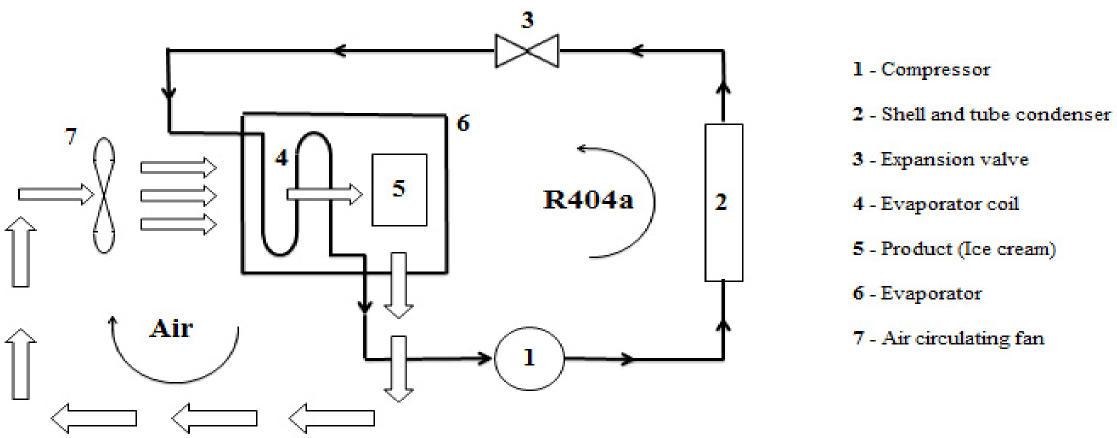

Fig. 1. Schematic of Air blast freezer

3.2. Experimental methodology

The methodology for experimentation was as following:

- The setup was run by switching on the power supply for no load conditions till the air achieve the desired temperature.
- Measure the velocity of air by anemometer.
- The ice cream boxes were placed in the air blast freezer. The arrangement and spacing between the boxes depend on the space available.
- The temperature sensor was placed at the centre of an ice cream box.
- The temperatures were recorded and the time taken for achieving the desired final food centre temperature was noted.

3.3. Uncertainity in measurement

The experimental uncertainities in the measurements conducted were as following**:**

- Temperature sensors ±1 ºC
- Pressure gauges ±0.01 bar.
- Anemometer ±0.01 m/s

4. Results and discussion

4.1 Analytical results

- The geometric shape of an ice cream box is one of the most important parameter taken under consideration. A cube is the best shape for the box type geometry and it takes minimum time for freezing. A cylinder takes half the time and a sphere takes one third time to freeze for a same characteristic dimension D but these shapes are not practically convenient to sell in the market. So a rectangular shape is the best option available for one liter ice cream packet.
- Orientation of ice cream box is also important. Flow parallel to the length takes more time than the flow perpendicular to the length as the boundary layer separation is more in case of the flow parallel to the length of box.
- For a uniform air distribution and better heat transfer, a spacing between the two consecutive boxes is desirable.

Table 1. An economic comparison of combined effect of velocity and temperature on total power (kW) for 90 minutes running time

Temperature (^{o}C)	**Velocity (m/s)**					
	1.5	**2**	**2.5**	**3**	**3.5**	**4**
-20	6.2790	6.4275	6.5895	6.7665	7.0305	7.0305
-25	6.6030	6.7515	6.9135	7.0905	7.3545	7.6545
-30	6.9270	7.0755	7.2375	7.4145	7.6785	7.9785
-35	7.2920	7.4405	7.6025	7.7795	8.0435	8.3435
-40	7.7370	7.8855	8.0475	8.2245	8.4885	8.7885

Generally for rapid freezing, the temperature of the system is taken towards the lowest possible range. This procedure increases the power consumption.

It is observed that an increase in velocity effectively decreases the total power. This also increases the fan power but the fan power is much lesser than the compressor power. From Table 1 it is observed that for desired time of freezing, total power is less in case of the increase in velocity than the decrease in temperature. So it is more beneficial to increase the air velocity than to decrease the air temperature.

As an example, for freezing time of 90 minutes, it is beneficial to select the combination (Velocity 4 m/s; Temperature -20 ºC) than the combination (Velocity 1.5 m/s; Temperature -40 ºC). It results in a power saving of 0.41 kW.

4.2 Comparison of experimental and theoretical results

To validate the theoretical calculations, experiments were performed for two different boxes having the different volume and dimensions.

The comparison of freezing time for both the boxes (box 1- 900 ml and box 2 - 1000 ml) in the exposer of an air at -25 ºC and velocity 1 m/s is shown in Fig 2.

The theoretical results are less than the experimental results since the conductivity of packing material is not considered in the theoretical calculations.

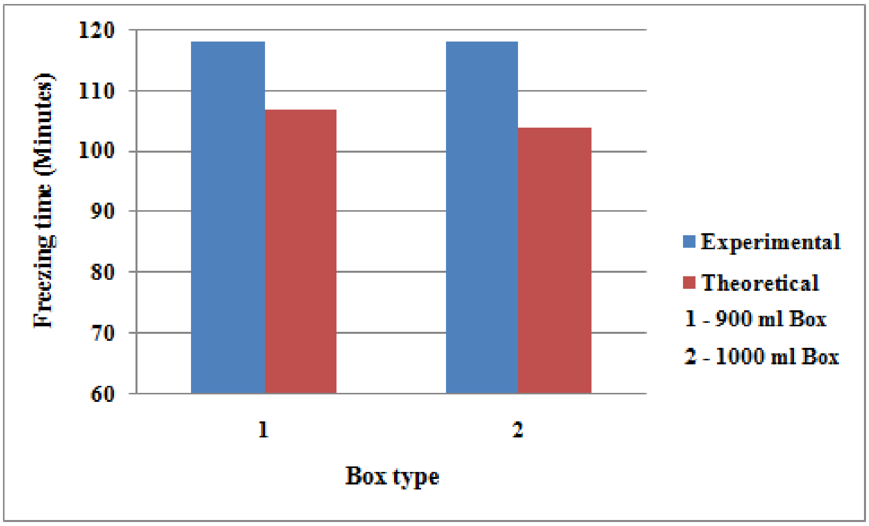

Fig. 2. Comparison of freezing time of ice cream boxes

5. Conclusions

Based on the study conducted, the following conclusions are drawn.

- The hardening of ice cream depends on various parameters but the shape and orientation of ice cream boxes along the flow plays a major role. The characteristic length (length parallel to the flow of air) is the most important factor. It should not be too long as due to the boundary layer profile created, it results in a decrease of heat transfer.
- The temperature and the velocity of the blowing air directly affects the power consumption. It is preferable to increase the velocity rather than decrease the temperature of blowing air. For the same freezing time, a combination of velocity and temperature should be selected in such a way that it contains maximum velocity (keeping pressure drop of air against the cooling coil in consideration) since the power consumption of fan is very low as compared to the power consumption of the compressor.
- The spacing between the two consecutive boxes is also an important parameter to be taken under consideration. For the uniform air flow, minimum 5 cm spacing is advisable.

Acknowledgements

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